REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
26-03-2013	FINAL	June 26, 2009 - December 31, 2012

4. TITLE AND SUBTITLE
Northwest Manufacturing Initiative

5a. CONTRACT NUMBER

5b. GRANT NUMBER
W911NF-09-1-0358

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Wood, William E.
Turpin, Robert
Quale, Thomas
Porgharibshahishahrebabak, Ehsan
Brown, Mattea
Nordstrom, Richard
Anderson, John C.
Fuller, Ellen A.
Evans, J. Rick

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Organization for Economic Intiatives, Inc.
1144 Gateway Lp Ste 203
Springfield OR 97477-7750

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army RDECOM ACQCTR - W911NF; 4300 S. Miami Blvd.; Durham NC 27703

Monitoring Agency: ONRRO; 300 Fifth Ave., Suite 710; Seattle WA 98104

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designed by other documentation.

14. ABSTRACT
This research evaluated increased welding productivity and resulting fracture properties of 500BHN hardness Mil-A-46100E, 16mm thick steel plate welded using a digitally controlled time twin wire Fronius welding system compared to single wire GMAW welding. Weld metal and heat affected zones were evaluated using Charpy and E399 fracture toughness methods. The influence of temperature, loading rate, CVN notch root radius, notch location, (weld and 2 heat affected zone locations) and quasi-static and dynamic E399 fracture toughness tests were evaluated to determine the influence of fracture test methods and welding procedures on toughness. Room temperature E399 tests, (CTS) were carried out under quasi-static and dynamic (4,000,000 and 8,000,000 pounds per second) loading rates. A K-type joint for single wire GMAW facilitated notch/crack locations in predominately individual coarse and fine heat affected zones and in the weld center line. Dual wire GMAW required a double bevel joint configuration to provide sufficient root pass penetration.

High productivity dual wire weldments achieved equivalent or improved toughness compared to single wire weldments. E399 toughness was not significantly strain rate or HAZ location sensitive. Pre-cracked CVN specimen toughness was significantly degraded relative to standard notched CVN data.

The goals of this grant may be organized into two areas, the Smart Automation Laboratory, and the Distance Manufacturing Masters program. The Smart Automation project aims to augment an existing laboratory in the area of agile manufacturing. The Distance Masters Program aims to leverage an existing MS in Mfg Engineering Technology to

INSTRUCTIONS FOR COMPLETING SF 298

service a wider audience and to tune the curriculum to service the needs of defense contractors

15. SUBJECT TERMS

Mil-A-46100, steel,GMA welding, Time Twin GMAW, Fronius,Charpy impact toughness, Precracked CVN,slow bend CVN, E399 fracture toughness, compact Tension, weld metal, heat affected zone, dynamic fracture toughness, gleeble fracture testing, hardness, robotics, education, manufacturing, automation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	UL	43	J. RICK EVANS
U	U	U			19b. TELEPONE NUMBER (*Include area code)* 541-756-5596

Northwest Manufacturing Initiative

Grant: W911NF-09-1-0358

Mr. Rick Evans, Administrative Representative

Organization for Economic Initiatives, Inc.
1144 Gateway Loop, Suite 203
Springfield OR 97477-7750

Prepared By:
J. Rick Evans and Ellen A. Fuller
Oregon Institute of Technology
Portland State University

31 December 2013

Final Report

Unclassified

US ARMY RDECOM ACQ CTR – W911NF
4300 S. MIAMI BLVD
DURHAM NC 27703

TABLE OF CONTENTS

Foreword

The Organization for Economic Initiatives, Inc. (OEI) is pleased to submit this final progress report for W911NF-09-1-0358. We have provided both performance and fiscal oversight for the entire project, including our partner organizations, through reports, site visits, and financial reviews. This report provides details on our collaborative research into both the evaluation of tensile and fracture properties of high strength structural and armor alloys and their weldments, as well as the development of agile, reconfigurable automated manufacturing environments. These research components address issues with the defense industrial base capability gaps and defense systems engineering gaps. Statements of the problems studied and summaries of the most important results can be found in the Executive Summaries of our collaborative partner organizations, including Portland State University and The Oregon Institute of Technology. The detailed research data from each of our partners can be found in the appendices.

Oregon Institute of Technology Executive Summary

This funding was aimed at two areas. These areas were the acquisition of equipment and supplies to equip a laboratory dedicated to the study of flexible automated manufacturing and to fund the work necessary to establish an MS degree program in Manufacturing Engineering Technology delivered by distance education technology.

Equipment acquisition was designed to provide additional work cells to allow for research and development into more agile combinations of equipment and to explore more flexible interfacing of cells, both from a software and hardware perspective, while maintaining reasonable costs. The cost aspect dictated that existing open market technology be used where possible.

The project was completed with the accomplishment of goals presented in the original proposal and within budget.

Portland State University Executive Summary

Conventional GMAW and advanced digital controlled Fronius Time Twin GMA welding was used to join 16 mm thick Mil-A-46100 500 Brinell hardness steel plate supplied by EVRAS-OSM. AWS ER70S-6 filler wire was used for all welds. Both single and dual wire welds were made with 4 passes, 80^{o}C preheat and interpass temperatures. Single wire heat input was 31KJ/in pass one and 1KJ/mm pass2-4 and tandem dual wire heat input was 0.9KJ/mm on pass one and 0.86KJ/mm on passes 2-4. The dual wire Time Twin GMA welds resulted in a 55 percent increase in productivity. This enhanced productivity would be further increased for thicker plate, since the dual wire root pass travel speed was the same as for single wire in order to ensure full root pass penetration for the single wire K-type joint configuration and the beveled K type dual wire weld. The joint configuration and the resulting welding procedure specification were designed to result in one side of the weldment having as straight a heat affected zone geometry as possible in order to enhance the placement of both CVN notches and fatigue pre-cracked E399 compact tension fracture sample crack tips in predominately coarse or fine heat affected zones. Weld metal fracture properties were evaluated as well.

In addition to evaluating productivity gains using precision digital Time Twin digital GMA welding system compared to single wire GMAW, the project evaluated the weld and heat affected zone toughness using several fracture assessment methods to determine if the assessment outcome evaluation would be influenced by test methods. Fracture test methods in the weld metal and in both the coarse and fine heat affected zones of both single wire and tandem wire GMA weldments included conventional CVN, fatigue pre-cracked CVN, Slow Bend conventional and pre-cracked CVN assessments. Dynamic CVN tests were done at multiple test temperatures. In addition to conventional quasi-static E399 compact tension fracture toughness evaluation, dynamic E399 tests were carried out at two loading rates,(4,000,000 and 8,000,000 pounds per second corresponding to approximately 600mm/sec and 875 mm/s displacement rates compared to 0.0076mm/s quasi-static loading for conventional E399 tests.)

E399 fracture results averaged, Hardness, Room Temp Standard CVN

Mil -A-46100 steel, 16mm thick plate base metal and GMA welded

Loading rate lbs/sec	Base metal ksi-in$^{1/2}$		Single wire GMAW ksi-in$^{1/2}$						Tandem wire GMAW ksi-in$^{1/2}$					
			weld center		coarse HAZ		fine HAZ		weld center		coarse HAZ		fine HAZ	
	Kq	K_{max}	Kq	K_{max}	Kq	K_{max}	Kq	K_{max}	Kq	K_{max}	Kq	K_{max}	Kq	K_{max}
50	86	98	67	106	71	103	69	97						
4,000,000	98	116	95	112	105	119	98	106	105	115	108	130	110	134
8,000,000	88	112	91	123	97	124	96	99	100	124	108	146	107	152
Hardness * knoop500gf	562		225		395		381		267		522		440	
Std CVN Rm Temp ft-lbs (J)	**34 (46J)**		**75 (102J)**		**48 (65J)**		**86 (117J)**		**81 (110J)**		**101 (137J)**		**83 (186J)**	

* hardness values are average hardness in each location for each pass after 4 passes completed

Appendix A – Oregon Institute of Technology Final Report

OIT Final Report for Army Research Lab Grant 2009-2011 (ARL 2009)

Abstract

The goals of this grant may be organized into two areas, the Smart Automation Laboratory, and the Distance Manufacturing Masters program. The Smart Automation project aims to augment an existing laboratory in the area of agile manufacturing. The Distance Masters Program aims to leverage an existing MS in Mfg Engineering Technology to service a wider audience and to tune the curriculum to service the needs of defense contractors

Executive Summary

This funding was aimed at two areas. These areas were the acquisition of equipment and supplies to equip a laboratory dedicated to the study of flexible automated manufacturing and to fund the work necessary to establish an MS degree program in Manufacturing Engineering Technology delivered by distance education technology.

Equipment acquisition was designed to provide additional work cells to allow for research and development into more agile combinations of equipment and to explore more flexible interfacing of cells, both from a software and hardware perspective, while maintaining reasonable costs. The cost aspect dictated that existing open market technology be used where possible.

The project was completed with the accomplishment of goals presented in the original proposal and within budget.

Project Report

This funding was aimed at two areas. These areas were the acquisition of equipment and supplies to equip a laboratory dedicated to the study of flexible automated manufacturing and to fund the work necessary to establish an MS degree program in Manufacturing Engineering Technology delivered by distance education technology.

Equipment acquisition was designed to provide additional work cells to allow for research and development into more agile combinations of equipment and to explore more flexible interfacing of work cells, both from a software and hardware perspective, while maintaining reasonable costs. The cost aspect dictated that existing open market technology be used where possible.

For the Smart Automation laboratory accomplishments include;

- Specification and purchase of two 6 axis articulated arm industrial robots,
    - Both of the robots have been purchased, installed and tested. The acquisition of these robots was the largest line item in the proposal. The first robot is a portable work cell centered on a small assembly robot. The entire work cell is mounted in an enclosure on casters and is powered by single phase 115v electricity. This equipment is ideal not only for teaching programming and integration in the laboratory, but also may be used at

remote sites for industrial outreach in robot programming, work cell design, fixture and tool design, and automation integration.
The second robot was selected for a larger work envelope and higher payload capacity. A Fanuc M16 robot was selected. The M16 was purchased as a bare robot as tooling development was part of this work.

- The work included construction of a work cell around the Fanuc M16 robot to simulate the installation of a window or windshield panel. The vacuum grip end effecter was fabricated in house along with the wooden fixture and the dowel to simulate sealant application. Plywood panels simulate the windows. This cell is shown in figure 2 below.
- Laboratory exercises were written and tested to integrate the robots into existing courses.


Figure 1: – Fanuc M16 robot & controller

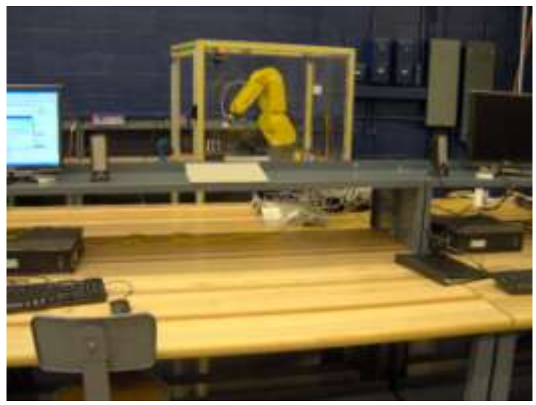
Figure 2:- Lab benches and Fanuc robot cell

- New lab benches and cabinets were specified, purchased and installed (See figure 3 below)


Figure 3: – Smart Automation laboratory

- The work planned in this project to integrate the software of new robots and older machines, is complete.

    - An important piece of this work has been the development of an interface between MS Robotics Studio and AutomationDirect Programmable Logic controllers. This work was described in a paper published in the proceedings of and presented at Annual Conference of ASEE 2010, Paper # **AC 2010-992-** Guttierez, Jose, Anderson, John, and Culler, David, "Development of a Generic Communication Service Between Programmable Logic Controllers and Personal Computers using Microsoft Robotics Developer Studio for Data Collection in Automated and Semi-Automated Manufacturing Processes.
- An older GMF 6 axis robot has been retrofitted using new control electronics and software. This robot will function as a teaching and research platform.
- A commercially available mobile robot chassis was specified and purchased. This frame was originally designed for use in robot fighting completion, but the combination of low center of gravity, strong frame, and high torque drive train also lends itself to material handling applications. This platform will be the basis for development of the autonomous material handling robot for the lab.
- A mobile robot platform was supplied to an undergraduate project team to develop guidance and target recognition software. The Computer Engineering Technology project team was supervised and mentored by Prof. Jim Long.
- Mathematical models of the individual robots and work cells were formulated by and used in graduate and undergraduate coursework led by Prof. Wangping Sun.

The Distance Masters Program aims to leverage an existing MS in Mfg Engineering Technology to service a wider audience and to tune the curriculum to service the needs of defense contractors. Accomplishments in relation to the Distance Masters Program include;

- Prepared and submitted documentation on the proposed MS degree in Manufacturing Engineering Technology by distance and obtained Oregon University System approval to offer the degree. Five courses in the initial offering have been identified. Marketing of the program will began in the 2009-2010 academic year and was continued in subsequent funding.

Summary

1. There has been one peer reviewed, published publication for this project.

   Guttierez, Jose, Anderson, John, and Culler, David, "Development of a Generic Communication Service Between Programmable Logic Controllers and Personal Computers using Microsoft Robotics Developer Studio for Data Collection in Automated and Semi-Automated Manufacturing Processes", Accepted for publication in Proceedings Annual Conference of ASEE 2010, Paper **# AC 2010-992**

2.
    a. 4 Graduate students supported in this period for summer work and 2 graduate students were partially supported during the academic year 2010-2011.
    b. No Post Doctorates supported in this period.
    c. Four faculty were supported (summer salary)

i. John Anderson, 2 months
ii. Wangping Sun, 1.75 months
iii. James Long, 1 month
iv. Brian Moravec, 0.75 months

d. 2 undergraduate students were supported half time for a total of 5 months.
e. 2 supported undergraduate students graduated in this period.
f. 5 supported graduate students graduated in this period of funding.
g. No other research staff were supported in this period.

Appendix B – Portland State University Final Report

Contents

1. Introduction

The introduction of digitally controlled pulsed gas metal arc welding has allowed significant improvements in precision controlled and increased productivity GMAW. Joining high hardness, 500 Brinell, steel plate, Mil-A-46100 presents challenges relative to welding procedures that enhance productivity, maintain toughness and avoid cracking. A dual Fronius Time Twin digital software controlled GMA power supply with integrated tandem electrode wire torch assembly system was used to evaluate both single wire and tandem wire GMA welds. 0.625 inch thick MIL-A-46100 plate was supplied by EVRAS-OSM. This thickness reportedly accounts for more than 75% of EVRAS-OSM's market for this grade of steel. Welding procedures for this high hardness plate presented challenges for customers. The welding portion of this project focused on first developing welding procedures for single wire GMAW and then welding procedures for the time twin dual wire Fronius GMA weldments. Dual wire welding generally offers the potential for increased productivity. However maintaining high quality weldments in MIL-A-46100 500HB water quenched plate could limit the increased productivity potential of the time twin system. The welding procedure development for the time twin dual wire GMAW concentrated on first ensuring a sound root pass with good penetration and the absence of any delayed cracking in either the single or dual wire weldments. Gains in productivity were bounded by the requirement to produce high quality defect free high toughness weldments. The second part of this project was to evaluate the hardness and fracture properties of both the single wire and the dual wire weldments, including weld metal and both coarse and fine grained heat affected zones. Since MIL-A-46100 plate is generally welded using an under-matched filler metal to avoid hydrogen induced delayed cracking, this project used AWS A5.18, ER70S-6 electrode wire.

All weldments were evaluated in the as welded condition. Variations of both standard CVN tests and E399 plane strain fracture toughness tests using compact tension test specimens were carried out on the weld metal and both fine and coarse grained heat affected zones. The intent was to determined if variations in fracture test methods would influence the basic fracture assessment results, influence conclusions relative to the single versus dual wire welding increased productivity procedures, and/or conclusions about fitness for purpose in the presence of crack like defects in the welds or weld heat affected zone regions. The latter could result from either weld fabrication defects or in service overload or fatigue loading. To evaluate the weld fracture properties traditional standard notch weld metal and heat affected zone CVN tests were carried out at temperatures ranging from 100^{o}C to -70^{o}C. The notch acuity influence was evaluated by fatigue pre-cracking CVN samples and loading rate effects were determined by comparing dynamic standard CVN E23 methods with slow bend CVN tests. In order to analyze the total absorbed energy an instrumented impact tup was used together with a high speed data acquisition system to capture the load impulse and hence separate the energy absorbed to max load and the crack propagation energy component that combine to account for the total absorbed energy. The dial energy, the total energy absorbed, was also obtained for all pendulum tests.

In order to evaluate full thickness fracture properties and a measure of critical flaw size and stress intensity relationships, room temperature E399 fracture toughness tests were carried out under quasi-static loading rates and under two intermediate rate dynamic loading rates for each weld zone. Conventional servo-hydraulic test systems are not suited for high loading rate fracture testing. First the

test is initiated from an at rest actuator and second the servo-valve is generally not able to deliver sufficient hydraulic oil to move the relatively large, 6 inch diameter, actuator piston at high rates. To overcome this limitation a Dynamic Systems, high flow model 3500 Gleeble dynamic test system was modified to accept E399 type compact tension fracture grips. Actuator displacement rates resulted in compact tension loading rates of up to 8 $x10^6$ pounds per second.

One significant problem associated with dynamic K_{1D} fracture toughness testing is securing the crack opening displacement, COD, gage on the front face of the test sample so that the gage response accurately records the crack opening displacement versus load. The Gleeble system was first modified to accept a traditional COD clip gage spring loaded and attached to front face notches on the test coupon. Attempts to secure the gage to the sample front face were not successful at high loading rates. A low mass extensometer design adapted from a Micro-Measurement application note for high strain extensometers was adapted for use as a COD gage. The gage was a single use gage, welded across opposite sides of the front face of the CTS sample and used a single strain gage bonded to the gage assembly. Each gage was calibrated against a traditional COD gage by mounting both on a CTS sample and loading elastically. This single use gage successfully measured the crack opening displacement during loading. 20,000- 50,000 hertz Data acquisition rates were used to capture crack opening and loads.

A significant challenge integral to each aspect of the research was the sample layout for each weld, notch location positioning, and cutting and precision machining all samples. While all weld metal notch locations were straight forward, locating notches in the coarse and fine grained heat affected zones require significant effort and precision. Significant welding joint detail development was required to as best as possible result in a near straight sided heat affected zone on one side of the weld. Developmental welds were sectioned and weld profiles characterized to develop notch location profiles based on surface measurements made on milled and etched top and bottom surfaces of each weldment. Due to the hardness of the plate, oversized coupons had to be excised by water jet cutting, then edges milled to square, then macro-etched to help locate notch position relative to the fine and coarse heat affected zone. Once the notch position was located the outside dimensions and holes were machined using a CNC mill. All notches were then added by wire EDM using the loading holes as reference positioning coordinates. All CVN samples were machined over length, the notch location identified after macro- etching the notch surface and then the final notch was added by precision grinding.

Collectively the major time and effort elements of the program were (1) welding procedure development, single and time twin dual wire GMAW for high quality welds with optimized weld cross section for sample preparation, (2) weld heat affected zone hardness and microstructure characterization, (3) fracture sample preparation, CVN testing including instrumented and pre-cracked, (4) dynamic fracture toughness testing, and (5) data analysis.

2. Experimental Procedure

2.1 Materials Armor Steel MIL:-A-46100 grade 500 (AR500), high hardness water quenched and tempered condition. The Ar500 was provided in 15.875 mm thickness and was austenitized at 1600^{o}F (870^{o}C) for 26 minutes and water quenched. It was subsequently tempered at 400^{o}F (204^{o}C) for 26 minutes and then air cooled. All plates were delivered in the finished condition from the same heat by EVRAS-OSM. The chemical composition is given in Table 1.

Base metal microstructure studies were carried out according to ASTM E112-10 [Standard Test Methods for Determining Average Grain Size]. In order to improve the contrast samples were tempered for 15 min at 450°F (232°C) prior to etching. The recommended reagent is 1 g of picric acid, 5 mL of HCl, and 95 mL of ethyl alcohol.

2.2 Welding and Fabrication

2.2.1 GMA Welds:

The specimen set consisted of Gas Metal Arc Welding (GMAW) process with two different conditions: Single Wire conventional GMAW and Tandem Wire GMAW. Heat inputs and joint geometry varied between single and tandem wire weldments. The GMA welds were fabricated with Fronius TimeTwin Digital System using TransPuls Synergic 5000 power sources. 1.11 mm diameter ER70S-6 welding wire was used to make all welds.

A straight HAZ Heat Affected Zone as possible was desired to maximize distinct HAZ zone (coarse and fine grained) microstructure notch and fatigue pre-crack sampling with a compact tension ASTM-E399 type test specimens and with Charpy -V- notch samples. ASTM- E23. Figure 1 shows the weld joint geometry for single wire welds. To do so, a modified K type butt joint was designed and used with all single wire welds. The edge of straight side of the joint was prepared and beveled, and the plated was tilted to 7^{o} to provide accessibility for welding and to guarantee full penetration on the root pass. Difficulties with lack of fusion at the straight side in tandem wire welds required using a double V butt joint. In order to find the best welding parameters that resulted in a sound weld, free of lack of fusion, procedure development welds were made on A36 structural steel. Welding was done perpendicular to the rolling direction. Figure 2 shows the weld joint geometry used for all tandem wire welds. The Time Twin welding torch dual wire configuration is shown in Figure 3.

All plates were preheated prior to welding. Interpass temperatures were maintained at the same degree as the preheating temperature. Preheat and interpass temperatures were determined in accordance with Ground Combat Vehicle Welding Code. Preheating was done with an oxyfuel cutting torch in two steps to ensure a uniform temperature through the plates. The preheat temperature was 80^{o}C for both Single and Tandem wire welds. K-types thermocouples were welded onto the top surface of plate to monitor both preheat and interpass temperatures for all welds, Figure 4.

In order to capture the welding thermal cycle and cooling rates at different locations near the fusion line, K-type thermocouples were embedded alongside the plate mid-thickness by making holes at different distances away from original root face. The thermocouples then were located at locations were

known as the locations near Weld Fusion Line, in Coarse Grain Heat Affected Zone (CGHAZ), and in Fine Grain Heat Affected Zone (FGHAZ) to capture heating and cooling curves during welding for these three regions. The single and tandem welding procedures are shown in Table 2 both single and tandem wire welds required 4 passes.

2.2.2 Calculated Heat Inputs

Heat input like preheat and interpass temperature, influences the cooling rate, which directly influences the mechanical properties and metallurgical structure of the weld and the HAZ. Heat input is the ratio of the power to the velocity of the heat source and was calculated as follows:

$$H.I\left(\frac{KJ}{in}\right) = \frac{V*I*60}{S*1000}$$

Where V is arc voltage, I is current and S is welding travel speed. The calculated heat inputs for all of the passes with single wire process are summarized in Table 2.

2.3 Toughness Assessment

2.3.1 Charpy Impact Testing

Charpy V-notch impact data were determined for L-T direction with respect to the plate rolling direction for four different zones, Base Metal, Weld Center line, WCL, coarse grained heat affected zone, CGHAZ, and fine grain heat affect zone, FGHAZ , over a temperature range from -70^{o}C to 100^{o}C. In order to reveal the weld cross sections and to place the notch in the exact location were the notch samples the most of the desired region (Weld center line, CGHAZ, and FGHAZ), all specimens were macro-etched in 10-percent Nital. Then notch locations were scribed in the weld center line and two HAZ locations and samples were cut to the final dimensions. Charpy tests were done using a Tinius Olson 264ft-lb capacity pendulum impact test system configured with a 10,000 lb(4,536kg) capacity instrumented tup. Charpy v-notch impact tests were made according to the ASTM-E23 [ASTM E23- Standard Test Methods for Notched Bar Impact Testing of Metallic Materials] specifications. For high temperature tests, a heated water bath was use while for low temperature testing down to -70°C, a methanol bath was used. Specimens were equilibrated at the bath temperature for at least 20 minutes prior to testing. An Instrumented LabView data recorder operating at 5Mhz was used to record the dynamic load impulse during impact. The data were analyzed to determine the Percent energy absorbed to peak load relative to total absorbed fracture energy. In all cases dial energies were also recorded. In most cases the instrumented data was in perfect match with charpy dial energy value. In order to locate the notch to sample as much as possible of the coarse and fine grained heat affected zones the CVN test coupons were machined over length and then macro etched using 10% nital to reveal the heat affected zones microstructures. The position for notch was scribed onto the over length sample, and the sample length then reduced to result in the notch location in the desired zone. Both standard CVN notches, 0.254mm root radius and fatigue pre-cracked notches were prepared. All fatigue pre-cracking was done using an Instron dynamic test system operating under load control.

2.3.2 ASTM E399 Compact Tension Fracture Toughness Tests

Fracture toughness tests were conducted under different loading rates ranging from quasi-static 0.0076mm/sec displacement rates, (50 pounds/sec loading rate) up to 885mm/sec displacement rates ($8x10^6$lbs/sec loading rate) using an Instron model1335 test machine, 900KN capacity and Gleeble 3500 high flow rate thermo-mechanical simulator modified to include E399 CTS sample grips and an Epsilon Technologies COD gage. The Gleeble test system was configured to slightly pre load the sample while positioning the actuator ram 30mm from the contact position. This allowed the ram to accelerate up to maximum speed prior to contacting the grip assembly and resulted in an impact loading condition unlike conventional servo hydraulic test systems which require a standing start and by system design have shave a much slower displacement rate than the Gleeble dynamic test system. Tests and post test analysis were carried out according to ASTM E399 [ASTM E399 - Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness KIc of Metallic Materials]. CTS specimens were carefully cut of the welded plates oversized using a waterjet due to the high hardness and then machined to final dimension using a CNC mill and carbide tooling. The samples were machined to sample as much as possible from each heat affected zone microstructure. Figure 6 shows the notch location in CTS specimens with regard to the welding direction. Prior to final machining, specimen's cross section microstructure was revealed by macro-etching in 10 percent Nital. Then notch locations were scribed in the weld center line and two HAZ locations, Figure 7. The specimens were machined to final proper dimensions and holes drilled referencing the notch positions. Lastly the notch was added using EDM referenced to the two loading hole positions.

2.3.2.1 Dynamic Crack Opening Gage Development

Conventional crack opening displacement gages, (MTS, Instron, Epsilon Technologies) are designed for quasi-static fracture testing and are held on by spring force to knife edges on the front face of a CTS sample. While excellent for slow strain rates, their offset mass and long attachment legs as well as the attachment mechanism precludes use under rapid dynamic loading. Even a reduce leg length gage does not have sufficient ability to withstand the dynamic impact load without excessive vibration which makes accurate load - COD gage data impossible to obtain. PSU designed, fabricated and individually calibrated a low mass high range COD gage, (LME). This strain gage low mass extensometer had a "top hat" configuration, figure 8, with a strain gage bonded to the top hat portion of the gage, Figure 9. Each gage was calibrated against a standard MTS COD gage, both mounted on a CTS sample and loaded in the elastic range of the CTS sample, figure 10. The LME was attached to the calibration sample using screws so that it could be removed. In order to attach and remain on the CTS sample under dynamic loading the gage was resistant welded to the front face of the CTS sample. Hence each gage was a single use gage. PSU made over 50 of these gages to test CTS samples from base metal, weld metal, fine and coarse heat affected zones at three strain rates for both single and tandem wire MIL-A-46100 welded plates. Data acquisition rates for the load were 50,000 hertz and for the COD gage was 20,000 hertz. A broken sample still in the Gleeble test fixture and an example of the welded on low mass extensometer are shown in Figures 11-12.

2.4 Fracture Surface Study and Fractography with SEM [Scanning Electron Microscope]

In order to determine fracture initiation-related features, reveal the nature of fracture at different temperatures/test conditions, examination of fracture surface in both CVN and CTOD test specimens was done using a FEI Sirion FEG SEM and Zeiss Sigma VP FEG SEM. The weld metal chemistry, and morphologies and chemistry of inclusions in the weld and base were analyzed by SEM-EDS analysis Fracture mechanism analysis, ductile rupture vs cleavage or quasi- cleavage analysis was analyzed in the sample mid-thickness near the end of the fatigue pre-crack to evaluate the fracture mechanism at the point of crack extension.

2.5 Metallography and Microhardness

Optical metallography was done to reveal the microstructure in different regions within base and weld metal. Samples were cut, hot mounted, polished and etched using 2% Nital. All grinding/polishing was done using a fully automated Struers Rotopol system to ensure consistent grinding and polishing Microstructural characterization of the welds was carried out in order to assess the effect of the welding thermal cycle on the weld and heat affected zone microstructure relative to the base material. Microhardness profiles across the welds and HAZ were evaluated using larger cold mounted and polished, (0.04micron) sections. An automated Struers Duramin microhardness test system microhardness with 500 kp and 15 seconds loading duration. Indentations every 200 µm to develop hardness profiles in the weld and heat affected zones. In order to find the best notch location in CVN and CTS specimens, The optical images and microhardness data were merged to identify the distance from the fusion line from which to offset the CVN and CTS notches.

3. Results

3.1 GMA Welding procedure

The modified K- type joint configuration used for single wire GMA welds resulted in a reasonably straight sided fusion line which in turn allowed notch location in the heat affected zones to significantly, 60%, in a single coarse or fine grained region. Figure 13 is a cross section image of the weld zone for a single wire weld. The larger GMA torch configuration for the tandem wire GMA prevented PSU from using the same joint configuration. A double-V- type joint allowed access for the root pass to ensure complete root pass fusion. However the joint configuration resulted in a much reduced straight fusion line which reduced the percentage of either the coarse or fine heat affected zone in any one notch location. Additionally weld metal was present on both surfaces of the compact tension full thick fracture toughness test specimens. Figure 14, a tandem wire weld cross section, shows the overlapping weld passes and the more complicated heat affected zone profiles. Using this geometry allowed only about 30% E399 fatigue crack sampling of either the coarse or fine heat affected zone regions. After the root pass subsequent passes using the Time Twin GMA employed a higher torch travel speed resulting in increased productivity and reduced heat input.

3.2 Hardness

Hardness profiles for single wire and tandem wire GMA welds are shown in Figure 15. The undermatched weld metal micro hardness was 225HK (500 gf load) and 267HK for the tandem wire welds compared to the 562 HK microhardness of the base material. The heat affected zone was separated into a near fusion line coarse grained zone (CGHAZ) and a second fine grained heat affected zone (FGHAZ) zone. Placement of all fracture sample notches and fatigue precracks in each zone was determined based on both hardness and metallographic analysis. Since all welds were made using the same welding workstation, same preheat and interpass temperatures, and the same preprogrammed welding parameters, the weld hardness and microstructure profiles were indistinguishable from weld to weld and at any point along the weld. The weld metal, coarse and fine heat affected zones of the tandem GMA weld were higher than that of the single wire GMAW, 267 HK versus 227 HK for the weld metal, 522 Hv versus 395HK for the CGHAZ, and 440HK versus 395HK for the FGHAZ, even though each weld had the same number of weld passes. The Tandem wire however had reduced heat inputs. The difference was most pronounced in the CGHAZ between the single and dual wire GMA welds. The coarse grain HAZ for the tandem wire welds was nearly the same as the base metal.

3.3 Microstructure

The weld microstructure for both single and tandem GMA weldments consisted of acicular ferrite containing grains decorated with proeutectoid ferrite on the boundaries. These columnar shaped prior austenite grain boundaries decorated with discontinuously nucleated proeutectoid ferrite are clearly visible in Figures 16-18. The coarse grain heat affected zone is also visible in Figure 16. Figures 19-21 at 500x magnification show the prior austenite grain size for the base metal and both coarse and fine grained heat affected zones. The fine and coarse grain sizes were the same for both single and tandem wire welds.

3.4 Fracture toughness

3.4.1 Charpy impact toughness

Conventional standard notch ASTM-E23 10mmx10mm square full size Charpy samples were prepared and represent conventional impact toughness assessment. Tabular and plotted data for conventional CVN impact tests are shown in Table 5 and Figures. Tabular values, Figure 5, are shown for room temperature and are averaged room temperature values. These data show that all weld metal zones for both single and dual wire GMA welds exhibit higher toughness than that of the base metal, and that the tandem wire higher productivity weld exhibited the highest weld toughness, more than 2x the base metal at room temperature.

In order to study the effect of notch root radius and to compare trends to E399 type fatigue pre-cracked full thickness tests, standard notched CVN samples were fatigue pre-cracked. Results are shown in Figures 22-30. In each plot the Charpy ft-lbs energy as measured by the dial energy readings were normalized by dividing the energy by the net cross section area, since the fatigue cracked CVN samples had a reduced ligament section relative to the standard CVN notch depth. In all cases even after normalizing by the net Area, the pre-cracked CVN data exhibited significantly less energy than did standard CVN notches. This is consistent with well known effect of the absorbed energy dependency on notch root radius until reaching a limiting root radius, between the standard 0.025mm root radius and a fatigue pre-crack radius. In all cases the weld metal and heat affected zones were tougher than the base metal. The tandem GMA welds exhibited high toughness, both standard notch and pre-cracked notch at temperatures down to -30^{o}C and were higher at -70^{o}C than the base metal at room temperature. Analysis of the dynamic load impulse displacement curve energy analysis captured using high speed data acquisition revealed that while the peak load was nearly the same for standard notch compared to pre-cracked notches, the area under the load- displacement curve was truncated for pre-cracked samples and accounted for the reduced total energy measured for pre-cracked samples.

3.4.2 E399 fracture toughness

Full thickness ASTM E399 compact tension specimens were tested per E399 test loading rate requirements and under rapid loading conditions. Rapid loading conditions were achieved using a Gleeble model 3500 configured with a high flow servovalve backed by a gas accumulator. Custom E399 grip fixtures and a custom low mass extensometer welded to the front face of each test sample allowed loading rates up to 8,000,000lbs/sec (3.6 x10^{6}kgs/sec) while maintaining accurate crack opening displacement measurements. Averaged results are shown in Table 5 and in Figures 31-34. The fracture toughness values, Kq and K_{max} for the single wire GMA weld were less than the base metal at quasi-static loading rates but increased in toughness with increased loading rates to greater than that of the base metal. At high loading rates the tandem GMA weld exhibited higher toughness in the weld center and both heat affected zones that did the single wire GMA weld even though the tandem wire weld had higher hardness.

Kq values are reported since only some test results met valid K1C test requirements. Generally those with lower Kq values were a result of non linear loading at lower load levels and hence a lower Pq value. The Kq values represent a lower bound value and the Kmax value the upper bound fracture toughness value. Ensuring valid plane strain tests would have required plate thickness approaching 25mm thickness but would not be representative of the majority of the thickness of MIL-A-46100, 500HB plate used. Typical thickness reported by EVRAS-OSM is in the range of 9-16mm thickness.

4. Discussion and Conclusions

The development of optimized welding procedures for single and tandem wire gas metal arc welded 0.625 inch (16mm) thick plate was dominated by trying to produce a weldment cross section geometry that exhibited as straight a side as possible to facilitate notch location in coarse and fine grained heat affected zones. The Fronius digitally controlled Time Twin welding system optimizes and determines voltage, wire feed speed, and amperage based on operator input parameters that include plate material and thickness, gas, wire diameter and type. Wire tip to work distance is adjusted by the operator. Dual inverted power supplies supply each wire independently and the welding controller adjusts the power characteristics for both wires according to Fronius preprogrammed control logic. Manual optimization of separate welding variables made welding procedure development impractical, although fine tuning of the voltage was possible. PSU had to develop the welding procedure specifications taking into account the precision controlled welding system preprogrammed logic. Consideration of productivity for single versus dual wire time twin GMAW was strongle influenced by efforts to maintain a straight sided fusion zone on one side of the single wire welds. The time twin tandem wire torch configuration required PSU to adopt a double V groove type joint. Four passes were used for both welding configurations but the weld area was larger for the dual wire weldment due to the joint geometry. Nevertheless the time twin process achieved significant productivity gains, 50-60%, as measured by increased torch travel speed. The use of higher heat inputs, if permitted when joining lower strength alloys would further increase productivity of the tandem wire time twin process. The use of a double -V- groove joint for both welding processes would have further increased the productivity comparison of the time twin compared to the single wire GMAW.

The heat affected zone hardness levels were comparable for the single and time twin weldments. However the tandem wire time twin GMA weldments exhibited somewhat higher hardness levels in both the weld and heat affected zones and is believed due to the reduced heat input per pass and correspondingly increased cooling rates for each pass. The increased hardness of the tandem time twin weld heat affected zones better matched the base metal hardness.

Complicating fracture assessment in specific fine and coarse heat affected zones is the very difficult challenge to produce a weldment fusion and heat affected zone geometry that allows a full thickness sample that samples only one weld heat affected zone microstructure. As the plate thickness decreases the challenge increases due to fewer weld passes required and the reduced ability to make successive passes vertically aligned. The dual wire time twin GMAW torch was larger to accommodate two wires in a single torch. Hence the joint geometry had to be modified for root access. This resulted in a more mixed microstructure, coarse and fine grained HAZ intersecting the crack path. The single wire weldment geometry allowed as much as 60% of the crack path intersecting a single HAZ zone, while the time twin dual wire crack path sampled only 30%f the coarse HAZ, the balance containing fine HAZ and weld metal. Assessment of HAZ microstructure generally requires at least 30% sampling of a single zone for comparative analysis. In the current research the 30% coarse HAZ for example represented the middle 30% of the fracture sample thickness - the plane strain portion of the sample thickness and the point of crack extension initiation. The weld metal portion in contrast was located on both surface

regions, the plane stress portion of the sample, and not a strong contributor to crack extension during testing and the determination of Kq.

Analysis of heat affected zone toughness was difficult for both CVN and K type samples. While fatigue pre-cracking was able to introduce cracks in specific desired locations, loading to failure resulted in the crack extension jumping to the weld metal in all cases. Since compact tension type E399 toughness considers the toughness at the point of crack extension and not crack propagation, the crack jump to the weld metal may not have significantly influenced Kq values. SEM analysis of crack extension from the fatigue pre-crack did not show significant fracture mechanism variations, all were microvoid coalescence, between weld zones or welding methods.

Comparison of pre cracked CVN toughness versus standard CVN toughness requires normalizing the absorbed energy by the sample net area, since the fatigue pre-crack reduces the ligament area and thus reduces the total fracture energy. Evaluation of standard and pre-cracked CVN energies demonstrated that the weldment weld metal and heat affected zones met or exceeded that of the base metal impact toughness as evaluated by either method, but that the damage tolerance of weldments containing cracks or crack like defects would be reduced.

Dynamic E399 fracture testing was made possible by the combination of the Gleeble high flow test system coupled to the design and fabrication of low mass high strain rate sensitive COD gages. These gages could be used for three point bend type fracture toughness testing using a drop tower which would allow fully dynamic fracture toughness testing comparable to dynamic CVN tests. At the outset of the program plans included evaluation of dynamic tear samples in addition to CVN and K type fracture tests. However the high hardness of the MIL-A-46100 500 HB plate and weld heat affected zones made pressing the dynamic notch tip impossible. E604 notch tip pressing is limited to samples less than HRC35. Dynamic tear samples were prepared with an EDM introduced main notch, but attempts to press the final notch tip were unsuccessful, even when using a carbide brazed notch tip pressing insert. Thus correlation of CVN and CTS type fracture results to DT data was not possible.

Gleeble loading rates of up to 8,000,000 pounds per second (3.6×10^6 Kgs/sec allowed intermediate loading rates to be evaluated. Using the gleeble high flow servovalve with gas accumulator actuator displacement rates of up to about 36 inches per second (900cm/sec) at loads up to the 22,000 pounds, (10kg). Additionally the actuator had a free travel length before contacting the loading grips. This allowed the actuator to develop an initial travel displacement rate of 80 inches per second (2,000mm/sec) at the moment of contact. Thus the initial loading rate was dynamic rather than the initial loading rate starting from zero for conventional systems

The fracture properties were not compromised by increased loading rates and actually increased relative to quasi-static loading rates. This increase was due to achieving a higher load during loading before the load become non linear suggesting that the high loading rates increased weld metal and heat affected zone yield strength by restricting dislocation flow induced plastic deformation. This suggests that even higher loading rates could result in further increased Kq values as the Kq load increases closer to K_{max} load values.

Conclusions

1. The Fronius Time Twin welding system resulted in high quality higher productivity weldments compared to single wire GMA.. The increased productivity was likely limited due to joint geometry considerations and further productivity increases can be expected under production conditions.

2. GMA welded single wire and dual wire weldment exhibited comparable or improved fracture toughness levels in all zones as measured by CVN or E399 type fracture test methods.

3. Dynamic loading rate K_{1D} tests exhibited toughness values at least as high as quasi-static loading rates. This may be due to higher applied loads prior to non linear loading at high loading rates resulting in higher Kq values. Significantly there was no loss of toughness as loading rates increased

4. The crack path jump from either heat affected zone initial crack location to the weld center likely resulted from the under-matched weld metal strength. Hence while initial crack extension in K type fatigue pre-cracked samples was in the desired HAZ location, crack propagation was likely complexly related to crack path jumping to the weld metal.

5. Introducing a fatigue pre-crack into CVN samples dramatically reduced CVN impact energies. The absorbed energy to max load was nearly the same as for standard notch samples but the propagation energy was sharply reduced resulting in reduced total energies. The results suggest that undetected production related manufacturing weld defects could play a critical role in promoting unexpected brittle fracture and that in-service delayed crack formation due to hydrogen, in service generated cracks by fatigue or overloads could also reduce fracture resistance as measured by CVN tests. Full thickness intermediate loading rate K_{1D} test results not loaded as rapidly as CVN dynamic tests, did not show any toughness degradation relative to the base metal containing comparable cracks.

6. Judging the most effective fracture method for assessing MIL-A-46100 weldments requires assessing the most likely in service crack formation potential and loading conditions. Quasi-static E399 type tests are not representative of normal service loading conditions. Fully dynamic loading CVN samples loading conditions are also not likely representative of normal in service structural loading conditions and may overly penalize acceptance criteria. Intermediate loading rate E399 data may be most representative of typical normal service operational loading rates. Assessing the most representative test and loading rate requires analysis of the system, stress intensity factors, compliance and anticipated in service normal loading rates. Neither CVN nor dynamic E399 tests simulate ballistic loading rates and may not correlate to anticipated behavior under extreme loading rates.

Table 1 Base metal chemical composition

Element	C	Mn	P	S	Si	Cu	Ni	V	Cb	Al	Cr	Mo	Ti	B	N
wt%	.29	.88	.005	.001	.45	.09	.39	.005	.002	.049	.50	.20	.056	.0015	.0078

Table 2 GMAW Welding Procedures

Weld Parameters	**Single Wire**	**Tandem Wire**
Welding position	1G(Flat)	
Weld Joint	Butt with 5/32 inch gap (4mm)	
Groove Type	Double Bevel	Double V
Groove Details	1/8 inch Land, 45^{o} Included Angle	1/8inch Land, 60^{o} Included Angle
Number of Passes	4	
Filler Wire	AWS A5.18, ER70S-6, 0.045 inch Diameter (1.14mm)	
Shielding Gas	98% Ar / 2% CO_2	
Backing	Ceramic Weld Backing Tape, 45^{o} Angle	Ceramic Weld Backing Tape, 60^{o} Angle
Shielding Gas Flow Rate	35 CFH	
Contact Tip – to –Work Distance	1 inch (25.4mm)	

Table 3 Welding Parameters - Single Wire GMA

Pass	Current I	Voltage V	W.F.S ipm (cm/min)	Travel Speed ipm (cm/min)	Preheat/Interpass °F	Calculated Heat Input KJ/in (KJ/mm)
1	296	29.9	305 (775)	17 (43)	175 (80 °C)	31.23 (1.22)
2	303	25.8	425 (1080)			27.59 (1.09)
3	283	26.4	535 (1359)			26.36 (1.04)
4	283	26.3	555 (1410)			26.26 (1.03)

Table 4 Welding Parameters - Tandem Wire GMA

Pass	Wire	Current I	Voltage V	W.F.S ipm (cm/m)	Travel Speed ipm (cm/m)	Calculated Heat Input KJ/in (KJ/mm)	Total H.I / pass KJ/in (KJ/mm)
1	Leading	185	20.6	355 (902)	23 (58)	9.94 (0.39)	24.04 (0.95)
	Trailing	230	23.5	450 (1143)		14.1 (0.55)	
2	Leading	190	21.8	355 (902)	27 (69)	9.20 (0.36)	22.00 (0.88)
	Trailing	240	24	450 (1143)		12.8 (0.53)	
3	Leading	190	23	355 (902)		9.71 (0.38)	22.23 (0.88)
	Trailing	230	24.5	450 (1143)		12.52 (0.49)	
4	Leading	192	23.3	355 (902)		9.94 (0.39)	22.29 (0.88)
	Trailing	226	24.6	450 (1143)		12.35 (0.49)	

Table 5 E399 Fracture toughness results averaged, Hardness, Room Temp Standard CVN

Mil -A-46100 Steel, 16mm Thick Plate

Loading rate lbs/sec	Base metal Ksi-in$^{1/2}$ (MPa-m$^{1/2}$)		Single wire GMAW Ksi-in$^{1/2}$ (MPa-m$^{1/2}$)						Tandem wire GMAW Ksi-in$^{1/2}$ (MPa-m$^{1/2}$)					
			weld center		coarse HAZ		fine HAZ		weld center		coarse HAZ		fine HAZ	
	Kq	K_{max}	Kq	K_{max}	Kq	K_{max}	Kq	K_{max}	Kq	K_{max}	Kq	K_{max}	Kq	K_{max}
50	86 (95)	98 (107)	67 (74)	106 (116)	71 (78)	103 (113)	69 (76)	97 (107)						
4,000,000	98 (108)	116 (127)	95 (104)	112 (123)	105 (115)	119 (131)	98 (108)	106 (116)	105 (115)	115 (126)	108 (119)	130 (143)	110 (121)	134 (147)
8,000,000	88 (97)	112 (123)	91 (100)	123 (135)	97 (107)	124 (136)	96 (105)	99 (109)	100 (110)	124 (136)	108 (119)	146 (160)	107 (118)	152 (167)
Hardness * knoop500gf	562		225		395		381		267		522		440	
Std CVN Rm Temp ft-lbs (J)	**34 (46J)**		**75 (102J)**		**48 (65J)**		**86 (117J)**		**81 (110J)**		**101 (137J)**		**83 (186J)**	

* Hardness values are average hardness in each location for each pass after 4 passes completed.

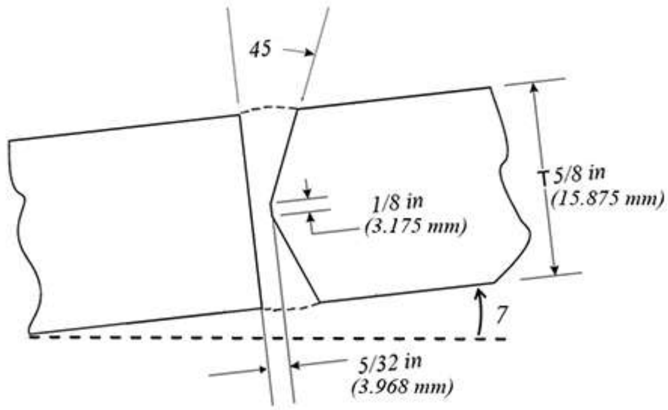

Figure 1 Single weld joint geometry

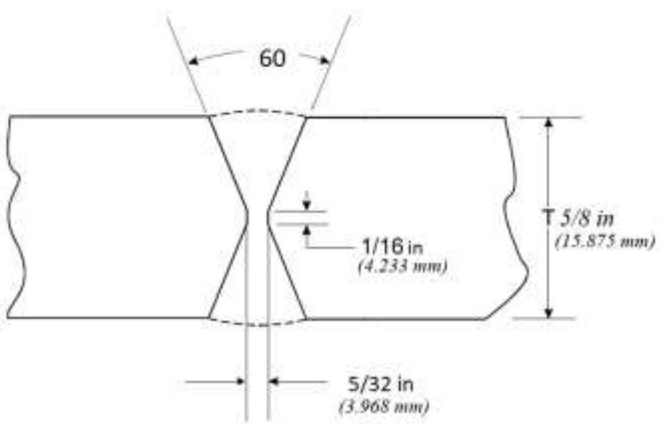

Figure 2 Tandem Wire Weld Joint Geometry

Figure 3 FroniusTime Twin GMA wire positions, after Fronius.com

Figure 4 Thermocouple position for temperature monitoring during welding

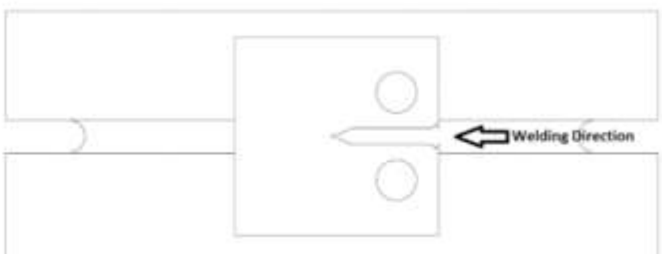

Figure 5 Location of E399 compact tension specimens, CTS, with regard to the welding direction

Figure 6 GMA weldments section layout for CVN tests

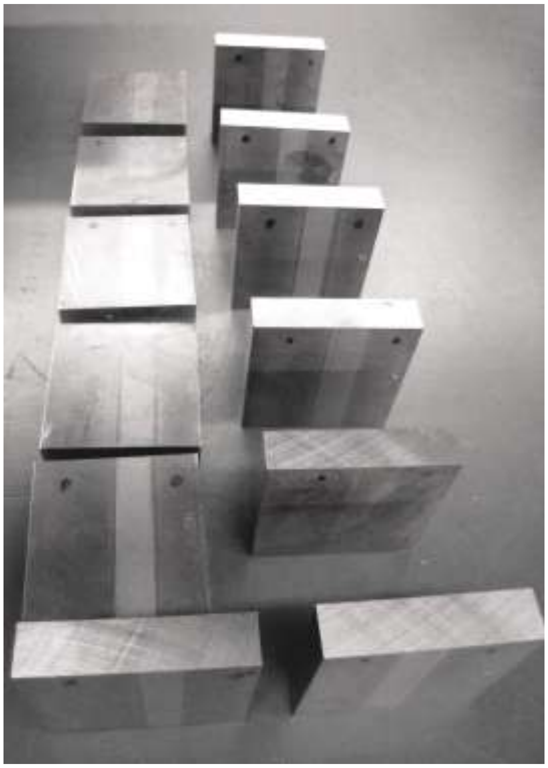

Figure 7 E399 CTS sample sections from GMA weld surface ground and macro etched to reveal weld metal and fusion line; CTS notches samples offset for HAZ fracture testing

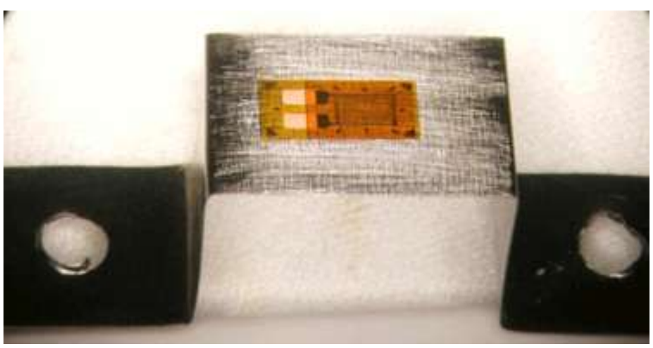

Figure 8 Low mass extensometer “top hat” configuration with strain gage; holes are for attaching to calibration CTS sample

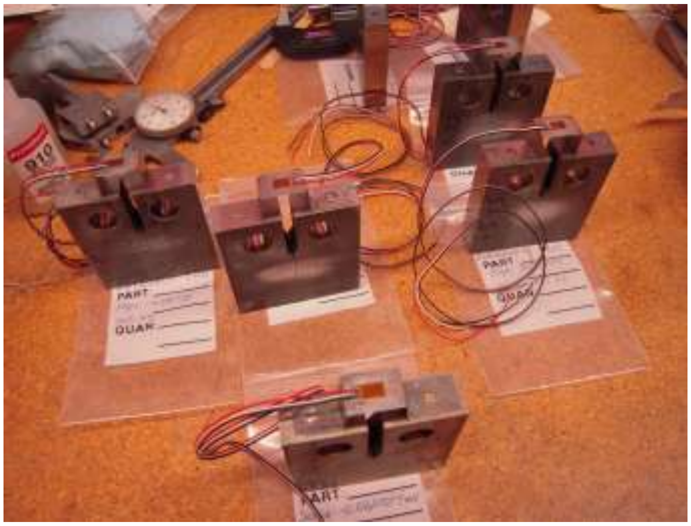

Figure 9 Low mass extensometers mounted onto E399 CTS weld test samples

Figure 10 Low mass extensometer mounted onto CTS sample along side of MTS COD gage. MTS gage used to calibrate each LME

Figure 11 Custom grip assembly integrated into Gleeble model 3500 test chamber; load and Extensometer data outputted to high-speed data acquisition system

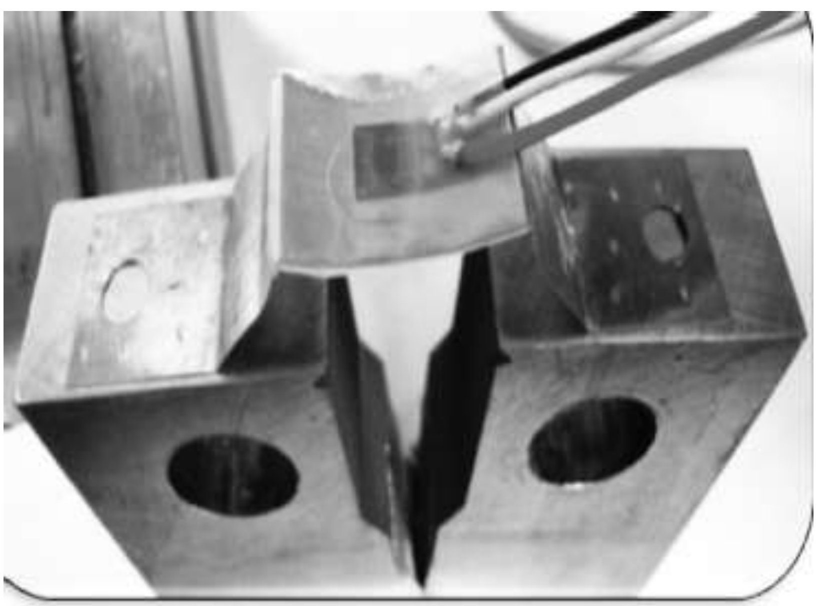

Figure 12 Dynamically loaded CTS sample with low mass extensometer still attached; LME welded to sample front face

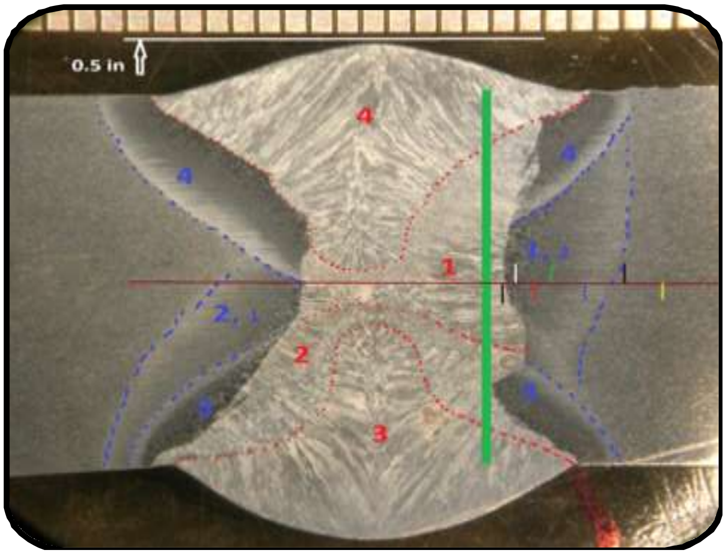

Figure 13 Single pass GMA weld macro cross section, vertical line indicates original plate faying edge; numbers indicate welding pass in weld metal and heat affected zones

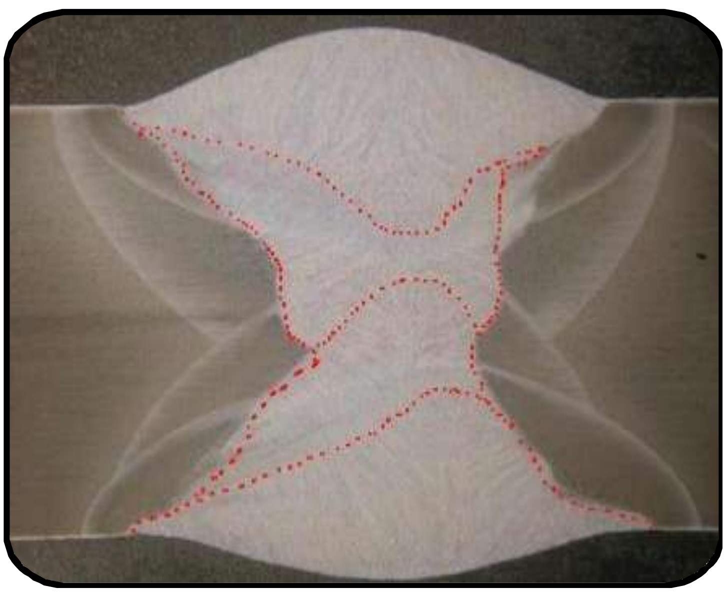

Figure 14 Tandem GMA weld macro cross section, dashed lines outline weld passes

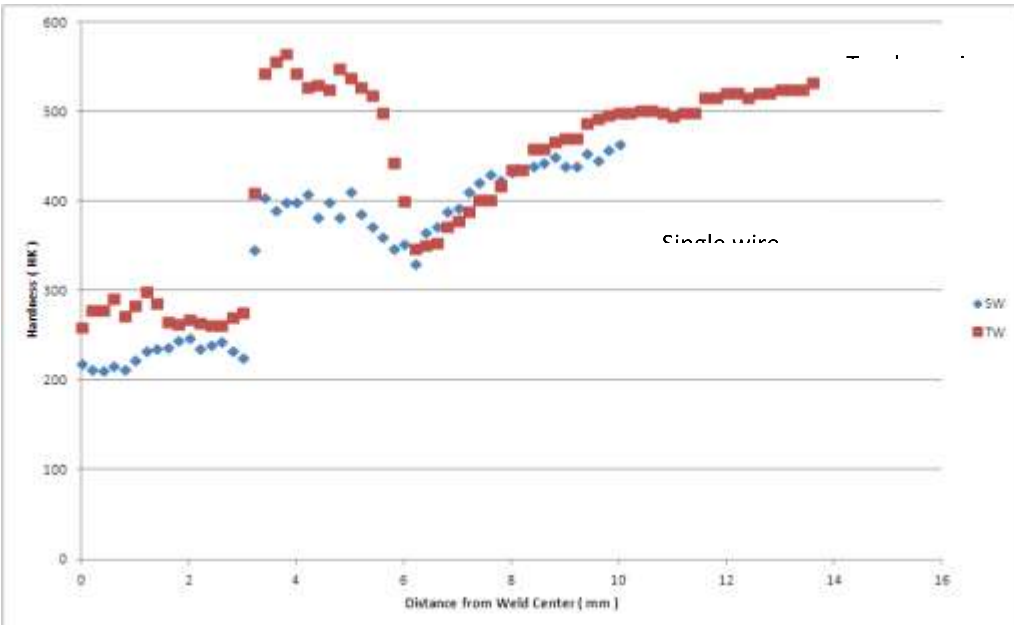

Figure 15 Knoop, 500gf load, hardness profile for single and tandem wire GMA welds; both coarse grained high hardness and fine grained reduced hardness regions between weld metal and base metal are visible

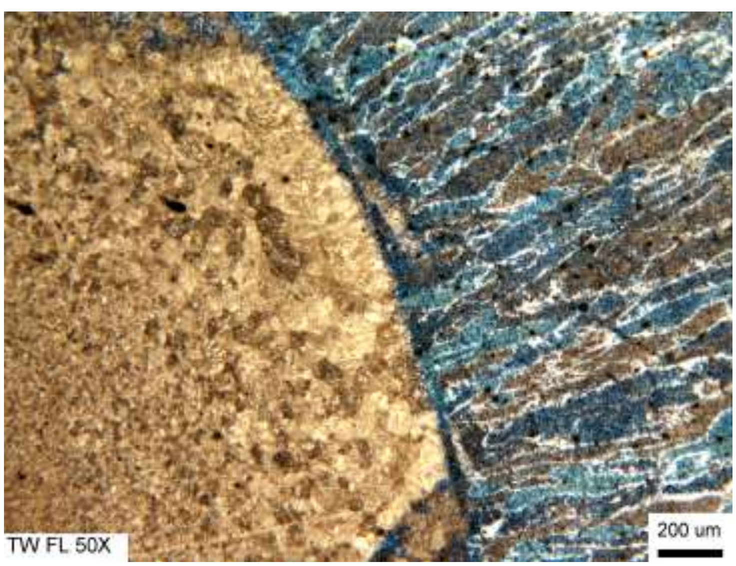

Figure 16 Tandem wire GMA weld metal and coarse to fine grain heat affected zones 50X original magnification

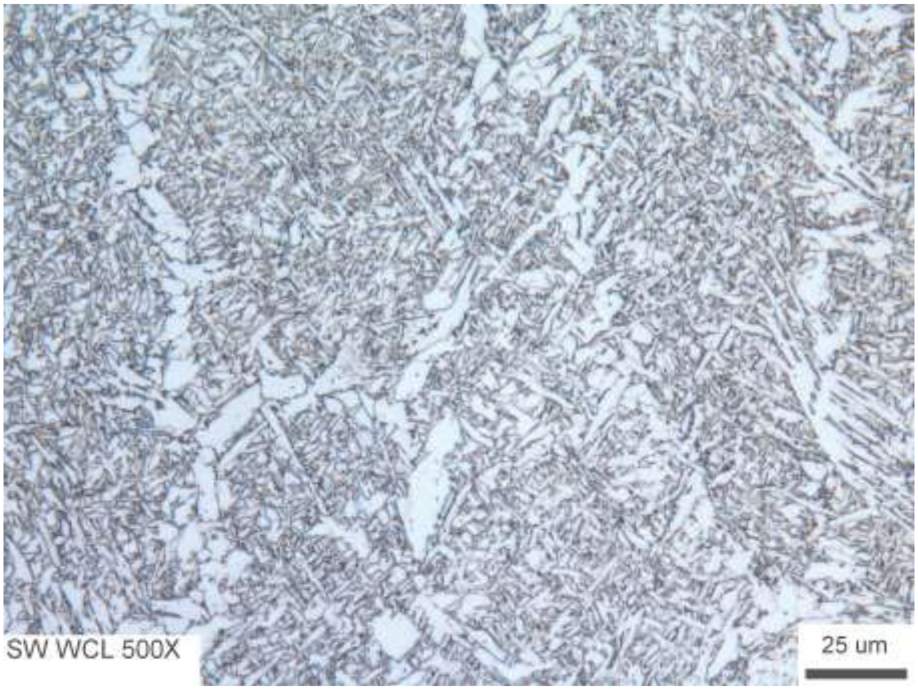

Figure 17 Single wire GMA weld metal containing acicular ferrite and proeutectoid ferrite, original magnification 500x

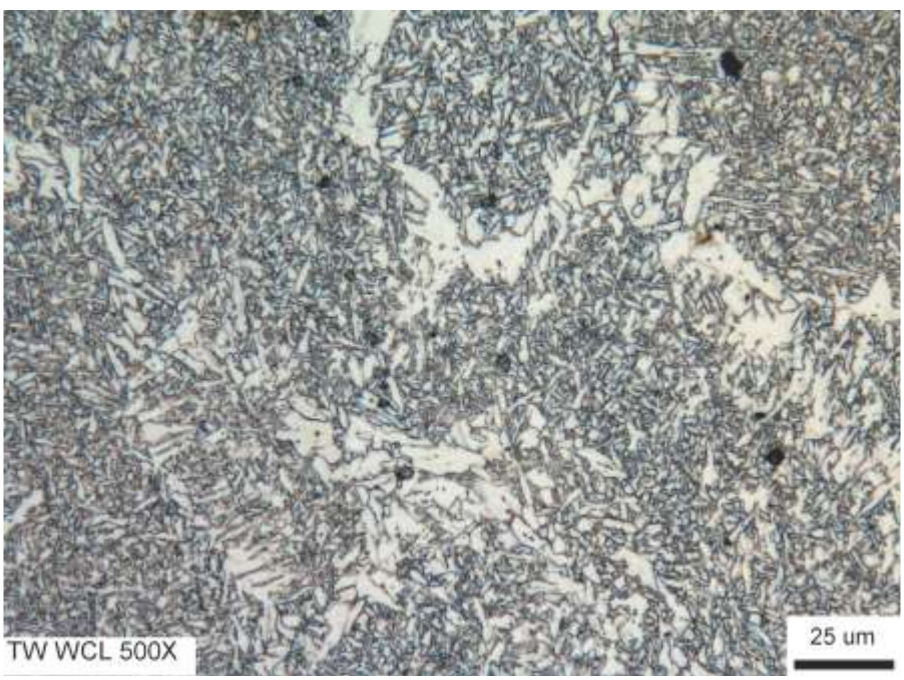

Figure 18 Tandem wire GMA weld metal exhibiting the same microstructure as single wire GMA weldments, Figure 17, original magnification 500x

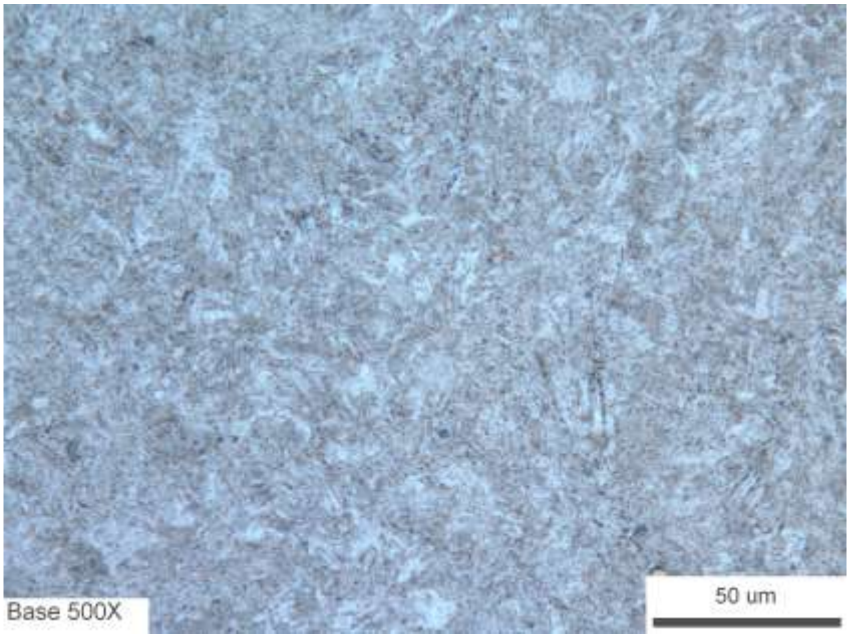

Figure 19 Base metal microstructure, original magnification 500x

Figure 20 Single wire GMA coarse heat affected zone, root pass, original magnification 500x

Figure 21 Single wire GMA fine grained heat affected zone, FGHAZ, original magnification 500x

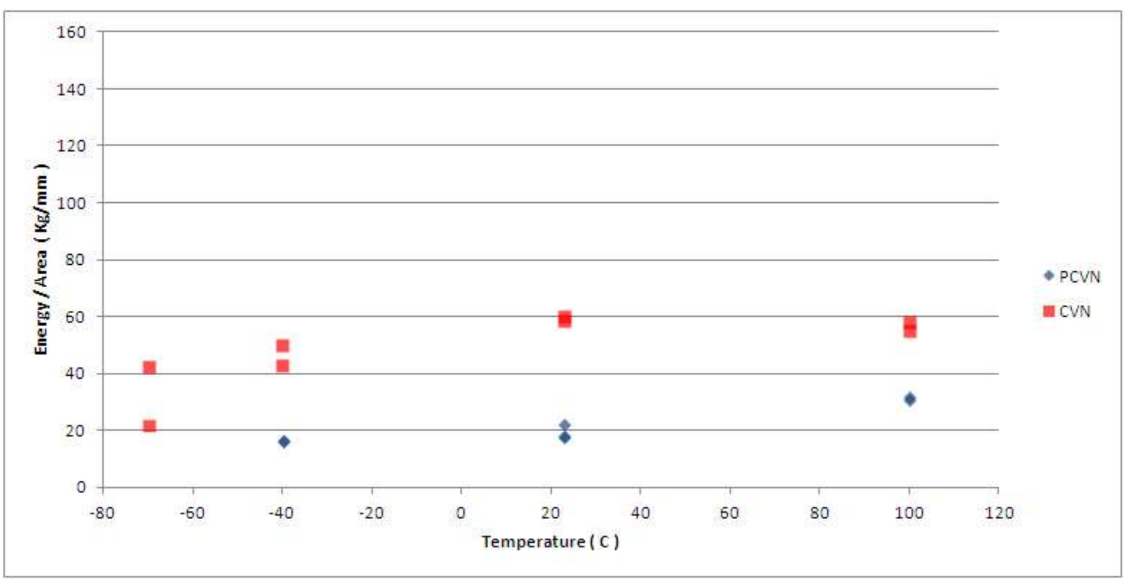

Figure 22   CVN energy divided by net section area vs. Temperature comparison base metal; standard CVN and pre-cracked CVN, PCVN

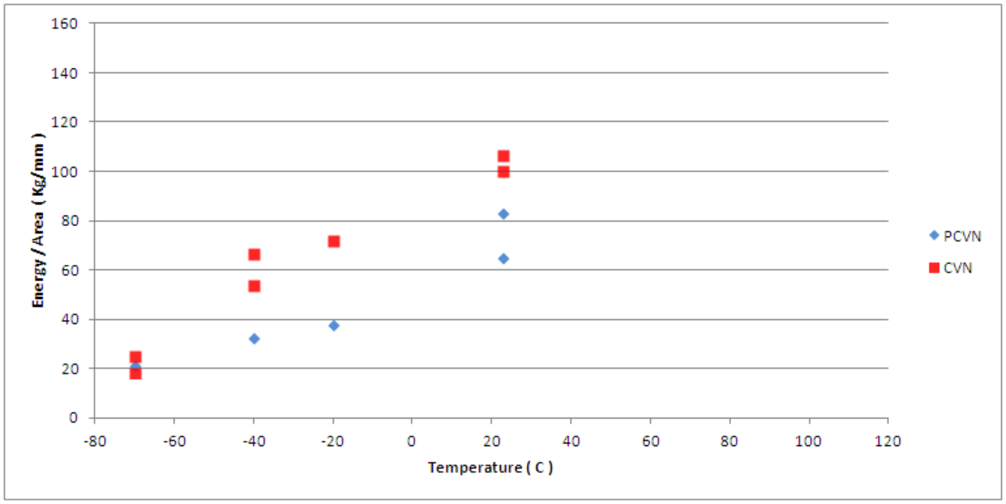

Figure 23 CVN energy divided by net section area vs. Temperature comparison single wire GMA weld center line notch location for both standard and fatigue pre-cracked notches

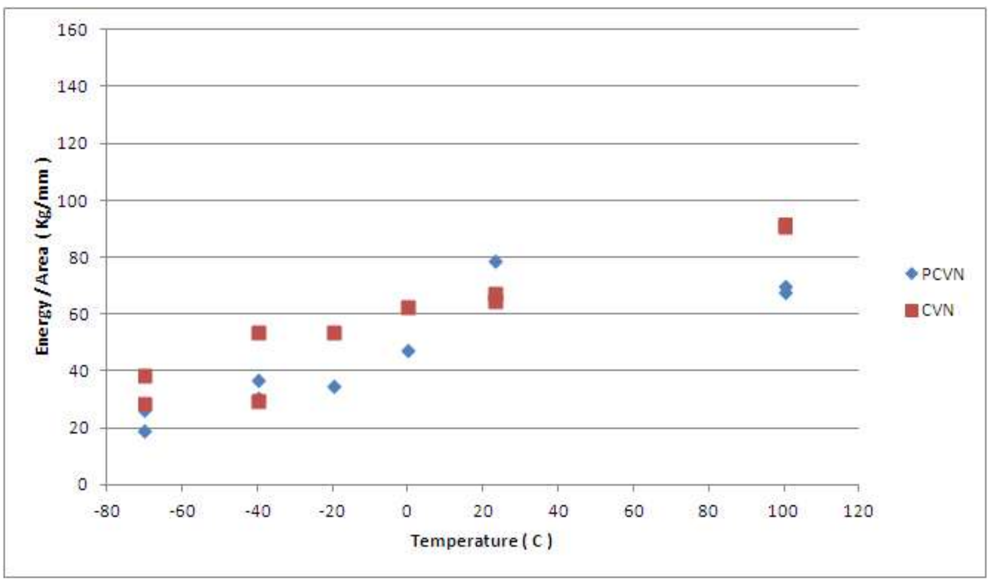

Figure 24 CVN energy divided by net section area vs. Temperature comparison single wire GMA coarse heat affected zone, CGHAZ for both standard and fatigue pre-cracked notches

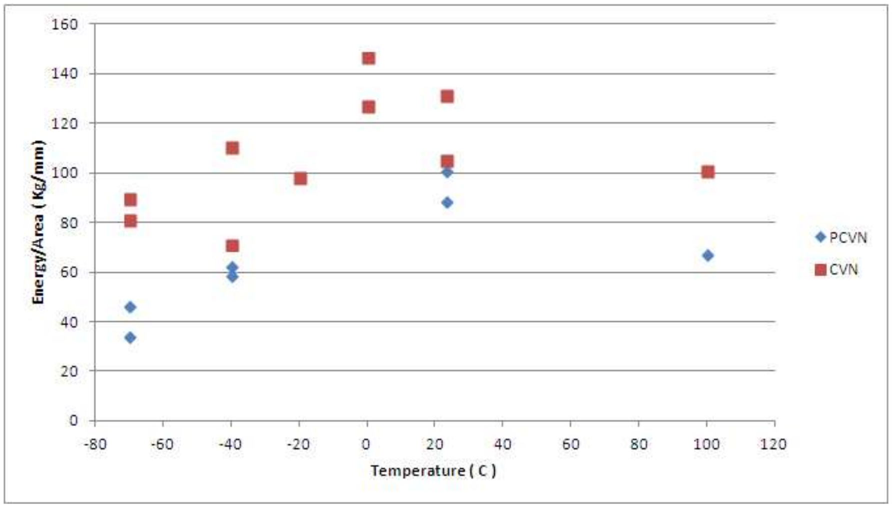

Figure 25 CVN energy divided by net section area vs. Temperature comparison single wire GMA fine grained heat affected zone, FGHAZ, for both standard and pre-cracked notches

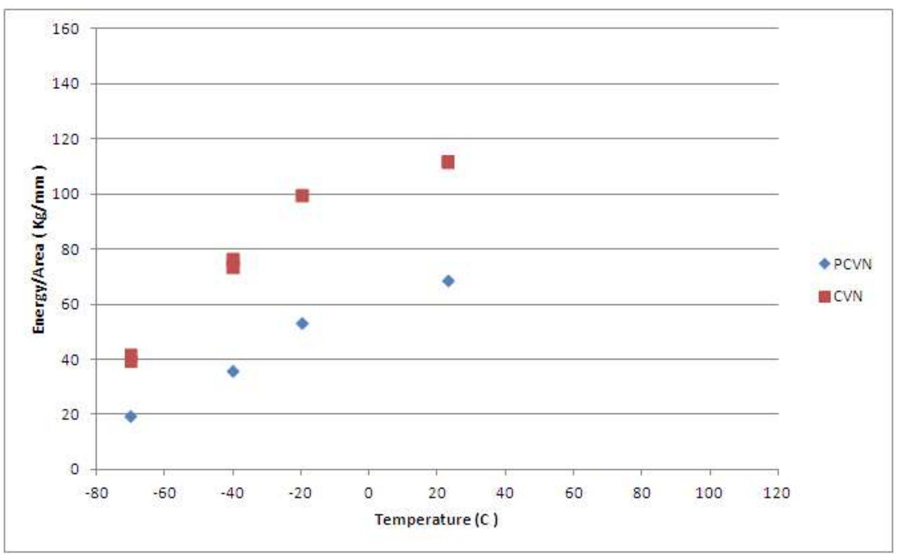

Figure 26 CVN energy divided by net section area vs. Temperature comparison tandem wire GMA, weld centerline notch location, both standard and pre-cracked notches

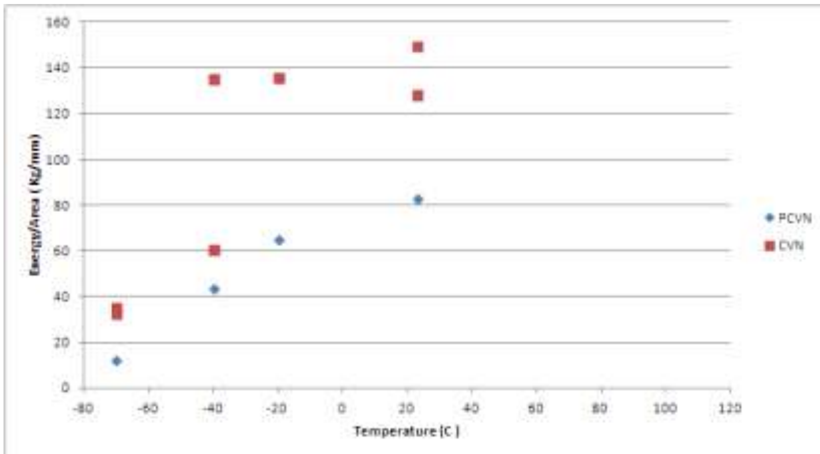

Figure 27 CVN energy divided by net section area vs. Temperature comparison tandem wire GMA, coarse grain heat affected zone, CGHAZ, both standard and pre-cracked notches

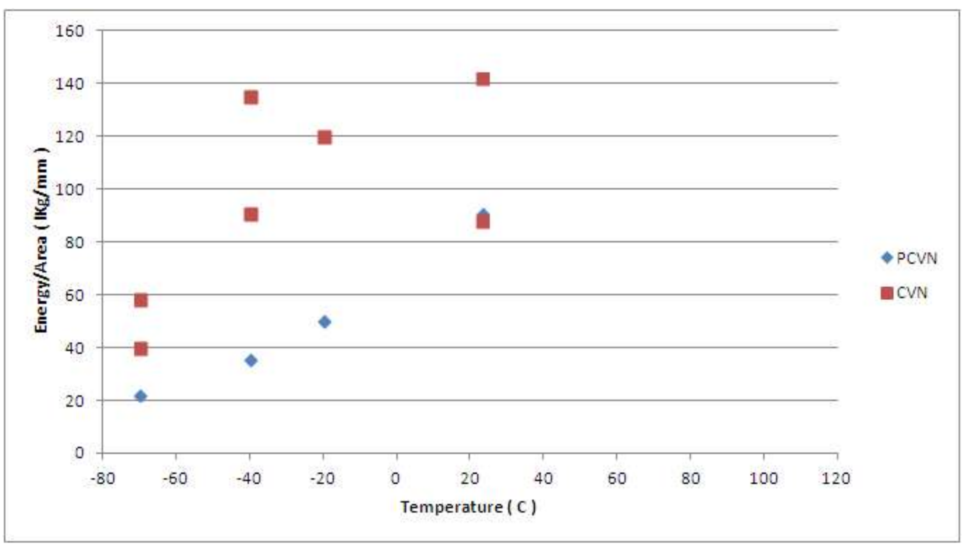

Figure 28 CVN energy divided by net section area vs. Temperature comparison tandem wire GMA, fine grained heat affected zone, FGHAZ, both standard and pre-cracked notches

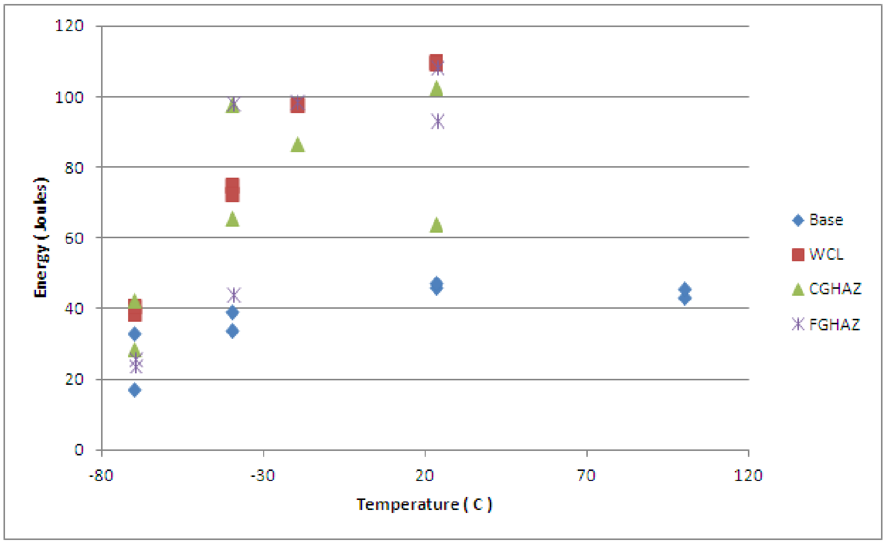

Figure 29 CVN energy vs. Temperature comparison base metal single wire GMA, standard notch, weld centerline, coarse, CGHAZ, and fine grain FGHAZ

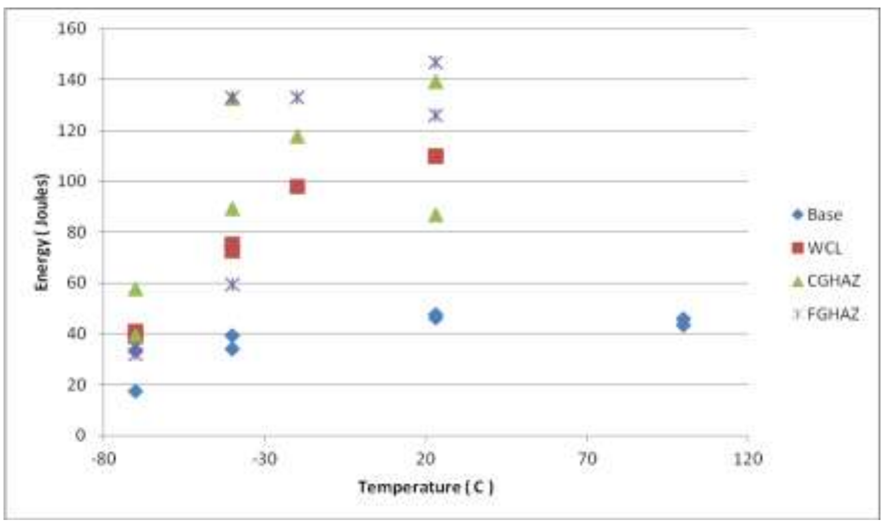

Figure 30 CVN energy vs. Temperature comparison base metal, tandem wire GMA weld centerline, coarse CGHAZ and fine grain FGHAZ

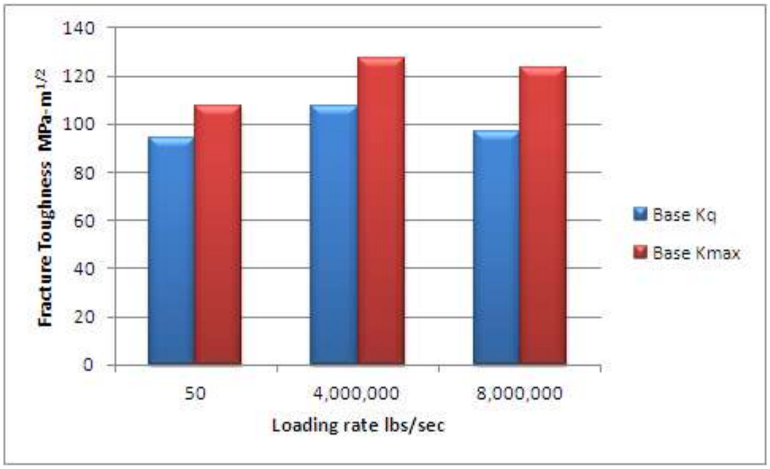

Figure 31 Base metal fracture toughness versus loading rate, individual test samples

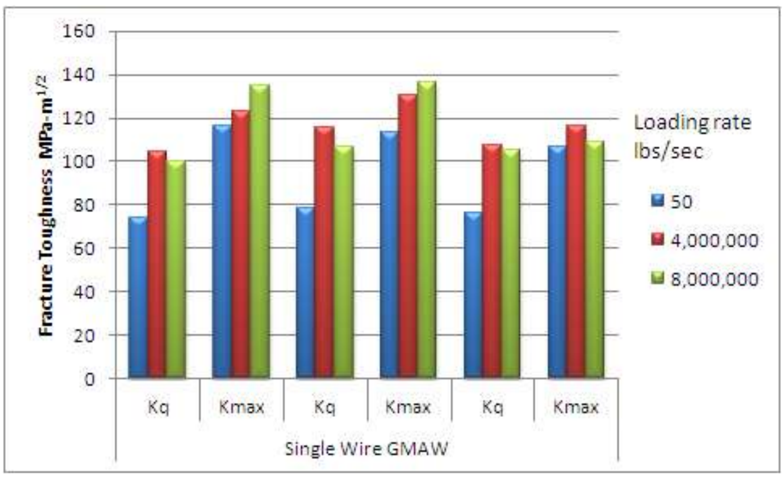

Figure 32 Single wire GMA fracture toughness vs. notch location and loading rate, averaged data

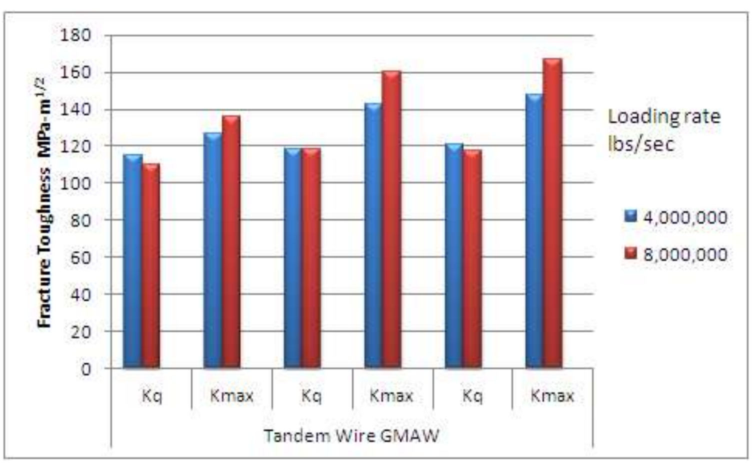

Figure 33 Tandem wire GMA fracture toughness versus location and loading rate, averaged data

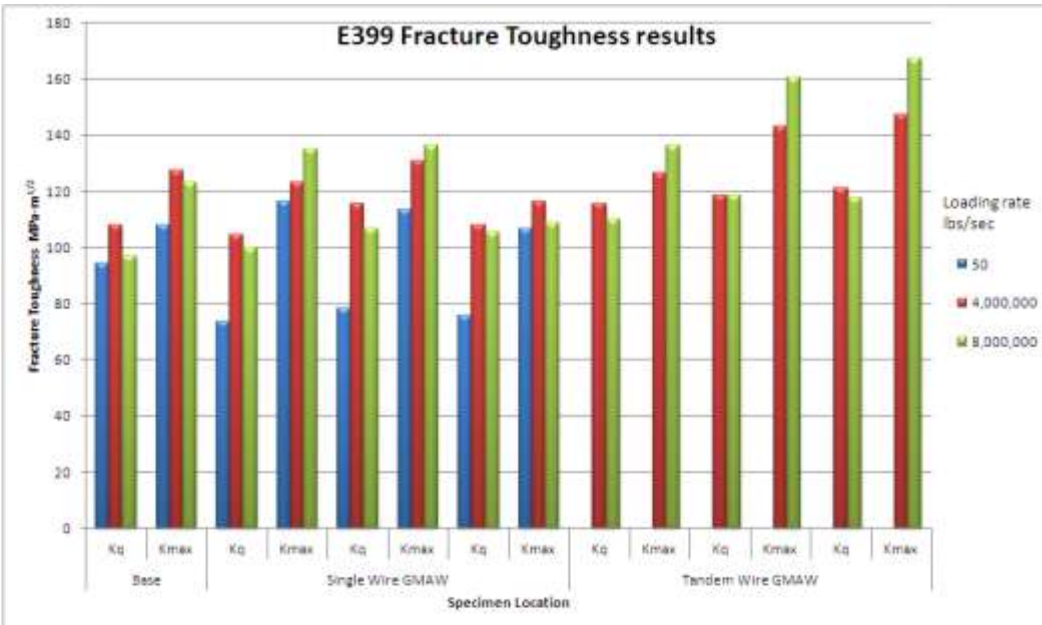

Figure 34 All E399 fracture data, averaged data for each test condition and location